LOCO with a Shipboard Lidar

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LONG-TERM GOALS

The long term goal of this research is to demonstrate an independent ability to use light detection and ranging (lidar) technology to survey and characterize the optical structure of the marine water column. The Sea Time Resolved Optical Layer Lidar (SeaTROLL) is a 532 nm lidar system designed for shipboard deployment to investigate the phenomenon of plankton formation into discrete thin layers. The phenomenonology of biological thin layers that can be investigated using lidar are the identification of layer regional distribution, frequency of occurrence, horizontal extent, vertical structure, temporal cycles, optical density, and potentially, unique optical characteristics that identify layer composition.

Biological thin layers are defined as concentrations of phytoplanktonic and/or zooplanktonic organisms occurring in a vertical thickness of several centimeters to several meters with contiguous horizontal extents on the order of kilometers. A solid body of work has established the existence of thin layers of biological organisms in both fjord and coastal ocean environments. Observations of these structures indicate that they are episodic and that their formation is induced by a combination of stratification and vertical shear (Cowles et al., 1998, Cowles, 2003). The initial studies of the physical, biological, and chemical processes associated with thin layers have shown that they are dynamic structures in the spatial domain, that they can persist for days to weeks, and that their biological and chemical rate processes are substantially more intense than those in the surrounding water column (Hanson and Donaghay, 1998; Dekshenieks et al., 2001). We do not know the extent of their presence throughout the marine environment, how important thin layers are to the overall productivity of the regional coastal ecology, or how they may interact with the oceanic ecosystem.

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In order to fully understand the impact of thin layer structures on coastal ecosystems and regional coastal-oceanic ecological interactions, the biological and chemical processes and process rates must be investigated within the context of their physical phenomenology. In order to understand and define the physical context for the formation of layers, high resolution spatial data is needed over the time period spanning their formation, evolution, and senescence.

OBJECTIVES

The objectives for the NAVAIR *LOCO* research effort are to:

- Develop a self contained, high (sub-meter scale, 2-10 cm) resolution 532 nm lidar system with a real time graphical user interface deployable from a mid-class oceanographic research vessel
- Collect field data on station and during ship surveys of optical stratigraphy in the upper water column identified by position and optical density
- Determine the system measured vertical diffuse attenuation coefficient (K_{sys532}) of the water column in the survey regions
- Correlate observed stratigraphy with:
    - in situ optical instrument inherent optical propery (IOP) data
    - suspended particle measurements
    - acoustic signatures
- Identify biological thin layer formations
- Detect and map the horizontal extent, the depth location, the vertical boundaries (when possible), and the temporal duration of biological thin layers

The objective to correlate the observed optical stratigraphy of the water column with profiles collected from ship and bottom moored profilers as well as autonomous underwater vehicle (AUV) and glider surveys is important to acquiring observations that allow the construction of a comprehensive and relevant dynamic model of the planktonic marine ecosystem. The ability to inter-compare and cross calibrate in situ instruments with a remote (shipboard, airborne or satellite) system on data collected simultaneously and in the same region provides an oceanographic tool for collecting a contiguous record of measurements that can aid in filling the temporal and spatial data gaps inherent in the traditional in situ profiling methods as well as extend the range and efficient routing of AUV surveys.

Defining empirical relationships between the in situ and remote optical data establishes a means for deriving environmental optical properties over geographically relevant areas of the ocean. This type of synoptic optical data is needed to predict the performance of Navy Electro Optic (EO) systems and to sea truth ocean color remote sensors. More significantly, by providing realistic initialization conditions, the data sets will significantly improve the performance of regional optical models.

APPROACH

The SeaTROLL lidar hardware was primarily designed and built by NAVAIR engineer Tom Curran in conjunction with Brian Concannon. The system software was developed by Brian Concannon and Dave Williams. The photo-multiplier tube (PMT) receivers were built and tested by Pavlo Molchanov, Olga Asmolova, and Ryan Springer. State-of-the-art, commercial off the shelf parts were chosen to create a lidar system with a high vertical resolution that would correspond to the 1-10 cm resolution achievable with the in situ instrumentation of the other PIs working on the *LOCO* program. To achieve this goal several system parameters were targeted: a 2 nanosecond wide laser pulse, a 250

MHz bandwidth optical receiver, a 5 giga-sample per second digitizer, and an INS/GPS system with pointing accuracies of less then 0.1 degree and position accuracies of less then 1 meter. The combination of the 2 ns wide laser pulse and the 250 MHz analog bandwidth of the PMT yielded a 0.2 m depth resolution.

The system consists of a pulsed Nd:YAG laser, an electro-optic modulator to chop the pulse width, transmit optics, polarization sensitive receive optics (2006 version), photo-multiplier tube based receivers, high speed digitizers in a PC chassis and a GPS/INS sub-system. The system specifications are listed in Table 1.

Laser Wavelength	532 nanometers
Laser Repetition Rate	5 Hertz
Laser pulse Width	7 nanoseconds
Chopped pulse Width	2 nanoseconds
Output beam Divergence	2 degrees full angle
Output Beam Power	5 millijoules
Receiver Field of View	5 degrees full angle
Receiver Filter Bandwidth	0.4 nanometers
Receiver Aperture	3” diameter
Detector Analog Bandwidth	200 Mega-Hertz
Digitizer Sample Rate	5 Giga-Samples per Second
GPS Accuracy	<0.5 meters
INS Accuracy	<0.02 degrees
System Polarization Ratio	1:50 co to cross
System Height above Water	8 meters

Table 1. SeaTROLL 2006 System Specifications

All system components were mounted on an optical breadboard for stability and placed in a watertight enclosure for mounting on the bow of a regional or ocean class oceanographic research vessel or ship (Figure 1). The purpose of locating the lidar system on the bow of the ship is to allow the system to observe the undisturbed surface ahead of the bow wake and to minimize exposure of the scientists and ships crew to the exiting lidar beam and specular reflections.

Figure 1. SeaTROLL 2005 During Assembly
[A side view of the optical breadboard with most of the system components attached. The laser is located on the far left corner of the bench the pulse chopper assembly and beam expansion optics are at center. The IMU is mounted to the right front corner. On the underside of the optical bench, one of the receiver tubes is visible in the front section and the mount for the computer is directly behind.]

Although the original system specifications remained the same (Table 1) with the exception of adding polarization filters on the receivers to collect the co-aligned and cross-aligned backscatter returns, the SeaTROLL hardware was reconfigured during 2006 to increase access to the system and maintain optical stability (Figure 2). The height of the optical bench was lowered to facilitate more direct access to the computer and receivers. Modifications were also made to lock the alignment of the beam through the chopper to increase the output energy and water column penetration of the emitted beam. Improvements were also made to stabilize the PMT electronics.

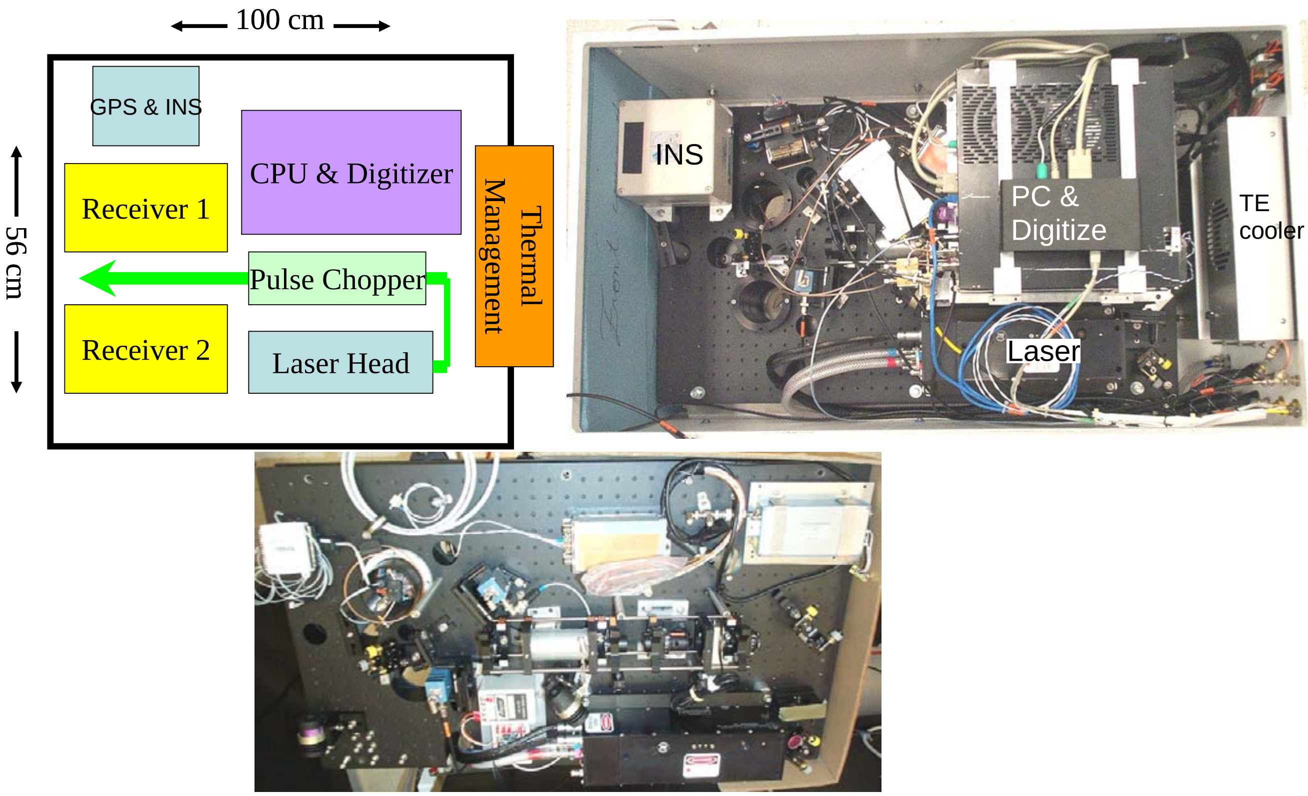

Figure 2. SeaTROLL 2006
[Identically oriented top down views of the system. A block diagram on the left shows the basic layout of the system components. Two thermo Electic (TE) coolers were used for system temperature maintenance and compensation. The bottom photo shows the laser and optical components mounted to the system optical bench. The photo adjacent shows the full implementation with the PC and digitizers mounted above.]

A Wetlabs ac-9 was set up in a flow-through configuration and connected to the ship's clean sea water intake port for the duration of the 2005 and 2006 field tests. The intake port is similarly located at approximately 5 meters below the water line near the bow of the R/V New Horizon (2005) and the R/V Thompson (2006). Total attenuation and absorption data were collected continuously except for periods during instrument calibration, power failure and hose clamp failure.

For both the 2005 and 2006 field tests, a combination of on station, adaptive, grid transect sampling, and edge mapping surveys were conducted in close collaboration with the collocated teams of Tim Cowles (in situ SLOWDrop Profiler) and Kelly Benoit-Bird (Bio-acoustics) (both at Oregon State University, OSU). Ship operations were coordinated through Chief Scientist Tim Cowles to the coastal team Alfred Hanson (SubChem Systems), Percy Donaghay (University of Rhode Island, URI), Margaret McManus (University of Hawai'i, UH), Van Holiday (BAE), Lou Goodman (University of Massachusetts Dartmouth, UMassDartmouth) and Dave Fratantoni (Woods Hole Oceanographic Institute, WHOI).

During the field test the lidar profiles were processed to show relative changes in water optical properties and to reveal water column structure in real time. Lidar maps were generated and shared with the other ship based PI's for use during the field experiment to identify and track observed.

Efforts were made during the deployments to visually look for coinciding trends in the profiler, acoustic, and lidar real time data. Correlations between the two dimensional structure of the real time SeaTROLL and acoustic data often seemed apparent, however obvious correlations were rarely if ever evident between the SeaTROLL and the OSU SLOWDrop profiler.

In order to use the raw data collected with a lidar system it must be converted into a form that can be compared to other methods of measuring the water column. In Figure 3(a), a simplified lidar return signal is shown versus depth. In a homogenous water column the lidar return is exponentially decaying versus depth and the rate of decay, or slope, of the returned signal is dependant on the optical properties of the water being sampled and the lidar system configuration. If the logarithmic slope of the lidar signal is plotted versus depth, as in Figure 3(b), a very good first order approximation of the relative change in the waters optical properties can be analyzed and compared. Visually, color coding the amplitude of the slope and plotting the profiles as a time series, as in Figure 3(c), allows one to quickly visualize and identify the vertical structure of the water column.

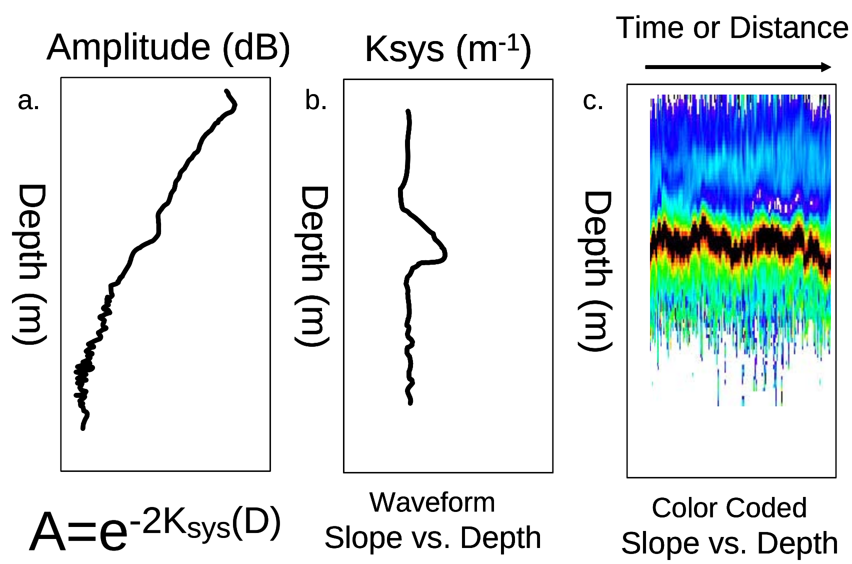

Figure 3. First level lidar processing
[The raw, exponentially decaying lidar waveform (left), taking the slope of the log of the waveform to calculate K_{sys} (center), color coding K_{sys} for visual cues (right).
False color image: Blue, K_{sys} = 0.1; Black, K_{sys} = 0.7]

For this extensive data set we plan to first classify the Ksys profiles to describe 4 water column types: Homogenous, Thin Strata within Homogenous, Optically Thick Interface and Slab on Slab. Figure 4 shows examples of each classification. For our analysis we are classifying a water column Homogenous if K_{sys} does not change abruptly from near the surface to the noise limits of the measurement. If an abrupt change in K_{sys} occurs, on the scale of 1 meter vertically, within the homogenous water column the profile will be classified Thin Strata within Homogenous. Optically Thick Interface Ksys profiles will abruptly end or drop to the noise limit due to intense absorption and/or scattering at a particular depth. Finally, the Slab on Slab category will represent water columns where a relatively large, several meters, vertical section of homogenous water lays on top of another large vertical section of water with different optical properties.

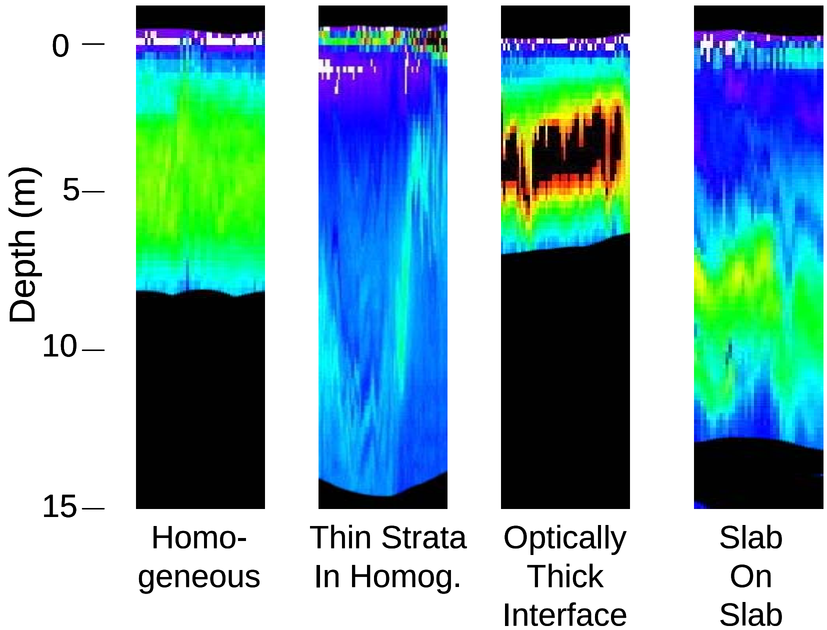

Figure 4. Color-coded K_{sys} plots showing the classification of K_{sys} profiles into four categories. [From left to right: Homogenous, Thin Strata within Homogenous, Optically Thick Interface and Slab on Slab]

Even though the color-coded K_{sys} is reasonable to evaluate by eye, the very large data sets (millions of profiles, hundreds of hours) require computer processing to data base the profiles based on similar optical layer characteristics. Once classified, the data can be grouped by time or location and pattern analysis can be performed. Systematic comparisons to the ac-9 flow-through, SLOWDrop and acoustics data can then be made. Again, due to the magnitude of the data sets, algorithm based statistical analyses are needed to correlate lidar and coincident in situ data to identify the relationship between the relative lidar optical density to IOPs or acoustics.

WORK COMPLETED

The FY 2005 effort successfully achieved the objective to design and build the SeaTROLL system and deploy it during the August 25 thru September 8 *LOCO* 2005 field test in Monterey Bay, California aboard the R/V New Horizon (Figure 5). An extensive data set (approximately 4 million lidar profiles) of highly resolved optical profiles were collected. In February 2006 preliminary results from the 2005 field test were presented in the "Thin Layers" session at the AGU conference, Honolulu, Hawai'i.

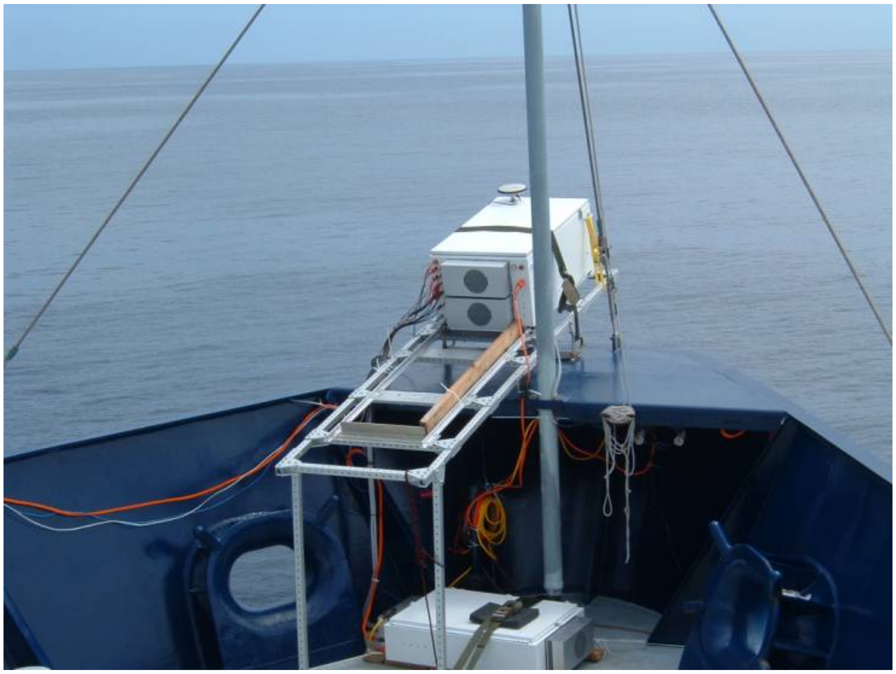

Figure 5. SeaTROLL mounted on the bow of R/V New Horizon during 2005 field test [Fully assembled SeaTROLL system mounted on rails and extended out over bow of ship]

In FY 2006 The SeaTROLL system was operated nearly continuously for 17 days from July 12 through July 27, 2006 in the Monterey Bay area aboard the R/V Thomas G. Thompson (Figure 6). Some data was collected during the transit from Seattle, Washington during July 9-11, 2006. In total, 5 million lidar profiles were acquired. The bulk of the data surveys and collection occurred in the Northeast quadrant of Monterey Bay (Figure 7) with the exceptions of a large area survey spanning the mouth of the bay July 20th and two 24 hour on-station time series July 22nd and July 26th. The SeaTROLL system collected reliable data to 2.5 KD which equates to 15m depth in the clearer waters over the canyon and 6 meters in the more turbid waters closer to shore.

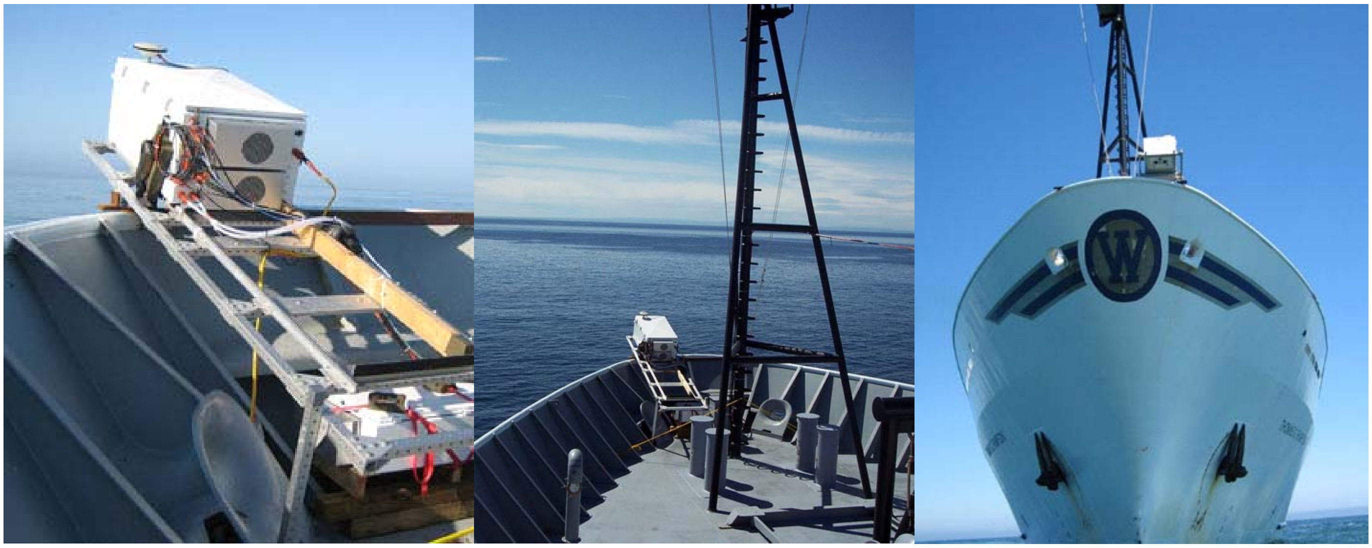

Figure 6. SeaTROLL mounted on the bow of R/V Thomas G. Thomson during 2006 field test [A series of photos show the installed SeaTROLL system. The leftmost photo shows the system mounted on its rails and deployed over the front edge of the bow. The center photo was taken from the bridge, looking towards the bow. The rightmost photo is taken from in front of the ship, looking up from the water. The front half of the system is visible.]

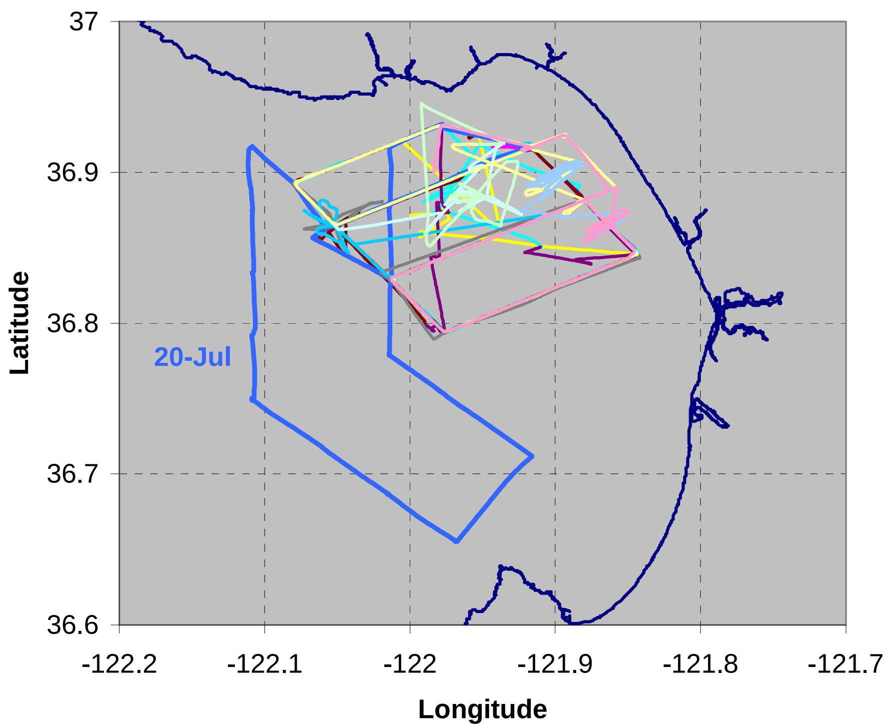

Figure 7. A track line map shows the positions where lidar data was collected for each day of the field test. The data collection was concentrated in the Northeast quadrant of Monterey Bay, with the exception of a large area survey spanning the mouth of the bay during July 20th

Descriptive data logs and for the 2005 and 2006 field tests were generated by the SeaTROLL software for all of the data grouped into 12 hour increments. Surface plots of the average water column K_{sys} were also generated by the SeaTROLL software. For the 2006 data, daily two dimensional K_{sys} plots were created for July 15-27, 2006 along with corresponding ASCII files with date, GMT time, latitude, longitude, and associated metadata. The waveform data were binned into1 minute increments at 20 cm resolution on all dates. On July 26 the data were also binned into 5 second increments at 20 cm resolution to resolve the structure of internal waves. Preliminary results were presented at the September 2006 Ocean Optics conference in Montreal, Canada.

Although the SeaTROLL component of LOCO did not receive ONR funding for 2007, a post-doctoral student working at the Naval Research Laboratory (NRL), Stennis performed an eight week work effort evaluating the data quality and post processing.the raw lidar waveforms. Dr. Wilhelmina Clavano focused on approaches to extract the water column lidar backscatter profiles from the surface return and noise floor. She researched and selected the approach of applying Wavelet theory to filter the lidar return waveforms, removing noise while minimally impacting the signal of interest. Dr. Clavano was able to validate the methodology by recreating the original waveforms from the deconstructed data and demonstrate that segmenting the signal using wavelet analysis maintained the sub-meter scale resolution of the SeaTROLL backscatter data significantly better than Fourier transform and boxcar averaging approaches.

The wavelet functions were investigated by comparing the local extrema of the wavelet coefficient functions to the local extrema of the raw signal. The resulting de-noised, segmented lidar waveform data were logarithmically fit and the resultant K_sys parameter was plotted against the backscatter depth range. Sufficient waveform groups were processed to determine statistically significant (one, two, and three sigma) error bars for identifiable depth ranges. The objective of this approach was to develop a quantitative measure to determine where the frequency of a signal was changing and to be able to subsequently segment these signal changes using batch processing routines.

Dr. Clavano was also able to begin working on applying continuous wavelet transforms to the SeaTROLL data to analyze frequency change, moving the concept from change in discrete waveform signal levels to continuous scale changes across time and space. Unfortunately, her effort was too brief to yield any significant spatio-temporal analysis of the Monterey Bay data before she moved on to a more permanent post-doctoral position in Canada.

The PI's requested and received funding for fiscal year 2008, at which time we pursued hiring a person with signal processing and large data set manipulation skills. At that time, and currently to date, the atmosphere at NAVAIR, Patuxent River makes it impossible to consider hiring Foreign Nationals such as Dr. Clavano. Prime in-house candidates in the EO and Special Mission Sensors competency with the needed skill set are extremely limited and their work efforts in FY07 and FY08 have been consumed with other Navy projects.

An ex-NRL employee was interviewed and hired to tackle the difficult task of post-processing the lidar data and to automate the process of layer detection and classification. The work began well with a continuation of Wavelet application to initially process the lidar waveforms. Regrettably, during the first quarter the situation deteriorated and it became evident that the individual was not competent for the tasking. The PI's spent their available time trying to keep the new hire focused on the overarching objectives, specific tasking, and analysis direction. However, the compound effects of an inability to conduct and comprehend the optical and oceanographic literature research and LOCO project background research required to come up to speed and meet the analysis objectives, to effectively communicate the data manipulation processes being undertaken, and to select productive analytical and algorithmic approaches. The new hire continued to get buried in minute details of the LabView programming environment. In short, the PI's failed to choose a candidate capable of moving the task forward, let alone complete it.

One of the FY08 objectives was to ingest the 2006 and 2007 lidar data collected during the LOCO program into a searchable data base. Utilizing an in-house resource, the 2006 lidar data set was imported into MySQL database, an open source database platform. Tools to access the data are provided for MATLAB, C and other common programming environments. Currently every lidar profile in the data set, at full vertical and time resolution is indexed by Latitude, Longitude and GPS time of profile. MySQL was chosen due to the ease of accessing the data and the ease of adding new indexing values, such as depth, amplitude of optical signature, and class of stratigraphy parameters. The PI's have a postential opportunity to leverage an in-house resource with 20+ years of experience in data processing and signal analysis, including lidar data analysis. However, utilizing his skill set will require having a dedicated and competent personnel effort working in conjunction with him and the data base expert. The PI's are still actively pursuing acquiring this and other advanced skill sets, however the current environment has not supported extending hiring offers and the requirement will most likely need to be fulfilled by the PI's.

RESULTS

In Monterey Bay at the end of summer thin layers appear to be a recurrent phenomenon, supported by the seasonal stratification and the episodic upwelling/relaxation cycles driven by alongshore winds. Overall the 2005 field survey provided a richer environment of thin layers present in the Bay, longer persistence, and more dynamic cycles of evolution and senescence. A significant portion of the 2005 thin layer phenomenon were not observed by the SeaTROLL system since most of the biological layers were at depths greater than 15m and the system was limited by having only one available receiver, optical misalignment of the beam through the internal optics, and resulting laser damage to some of the internal optics. SeaTROLL improvements during 2006 reduced system noise and secured the optical alignment and ease of in field adjustment which enabled the system to retrieve deeper data and improved the resolution of KD.

All lidar systems face the challenge of capturing the tremendous dynamic range of the optical return signal, several orders of magnitude, in a very short period of time, a few hundred nanoseconds. One measure of a lidar systems performance is the number of KD's the system can measure from the peak return signal to the system noise limit, where K is the system attenuation coefficient (K_{sys}) and D is depth. In clear waters, K_{sys} is low and signal can be acquired from deeper depths and in more turbid waters Ksys is high and signal is only received from shallower depths. Therefore KD as a measure of system performance is normalized for waters optical properties. The SeaTROLL system collected viable signal to 2.5 KD due to limitations on the digitizer and photo-detector limitations. Spectral leakage creating an artificial tail on the return wave form resulted in an increased noise floor.

For SeaTROLL this system 2.5 KD equates to 15 meters depth in the clearer waters over the Monterey Canyon and 6 meters closer to shore. For a qualitative visual reference, Figure 3 shows a picture of the R/V Thompson's CTD cage near the water surface. In the coastal water case, on the left, one can not see the bottom of the 2 meter tall cage. In the clearer water case the bottom ring and the water sample tubes fairly clear.

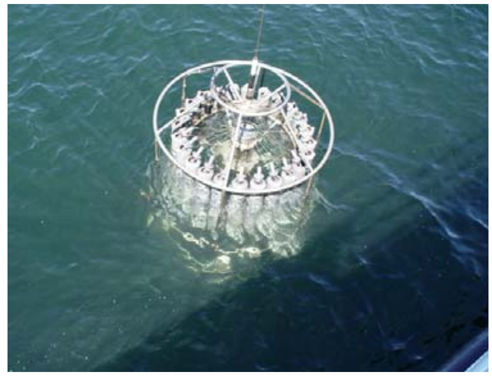

Figure 8. A simple illustraton of different water types shown by comparing the details of the R/V Thompson's partially submerged CTD cage. On the left, the more turbid case, the structure of the cage is blurred. On the right, a less turbid case, the bottom ring, while wavy due to the surface, is clearly visible.

Difficulties in comparing measurements made at the bow of the ship versus those made at the stern primarily include the time lag between the sampling the same column of water and the possibility that the current flow will be lateral to the bow-stern axis, so that there is no possibility of sampling the same water column. Further, on a large ship like the R/V Thompson, the station keeping thrusters are powerful enough to disturb and mix the upper water column. A fundamental limitation of the K_{sys} classification process is the lidar data has a relatively shallow vertical view of the water column when compared to in situ and acoustic measurements. These classifications may not always coincide with other instruments entire view of the water column being sampled. However, there should be agreement for the common section of the water column that all instruments can sample.

During the 2006 field test in Monterey Bay a variety of water types and structures were observed. In Figure 9, a 24 hour period of lidar K_{sys} data collected during a large area survey from 00:00 hours July 20th to 00:00 hours July 21st (GMT) is depicted. The vertical black lines are periods when lidar data was not available. The data was averaged to 1 minute time bins and 0.2 meter depth bins. The water column ranged optically from moderately turbid at the beginning of the period to clear at 06:00 to extremely turbid towards the end of the period. Thin, weak vertical structures occur starting at 09:00 and strong layer structures were observed at 16:00. It should be noted that 1 minute binning may obscure short time-varying features such as the disturbance of a layer due to an internal wave. In Figure 10, a 1 hour plot of K_{sys} binned to 1 minute is compared to a 10 minute plot of K_{sys} binned to 5 seconds. The group of internal waves is obscured with 1 minute binning.

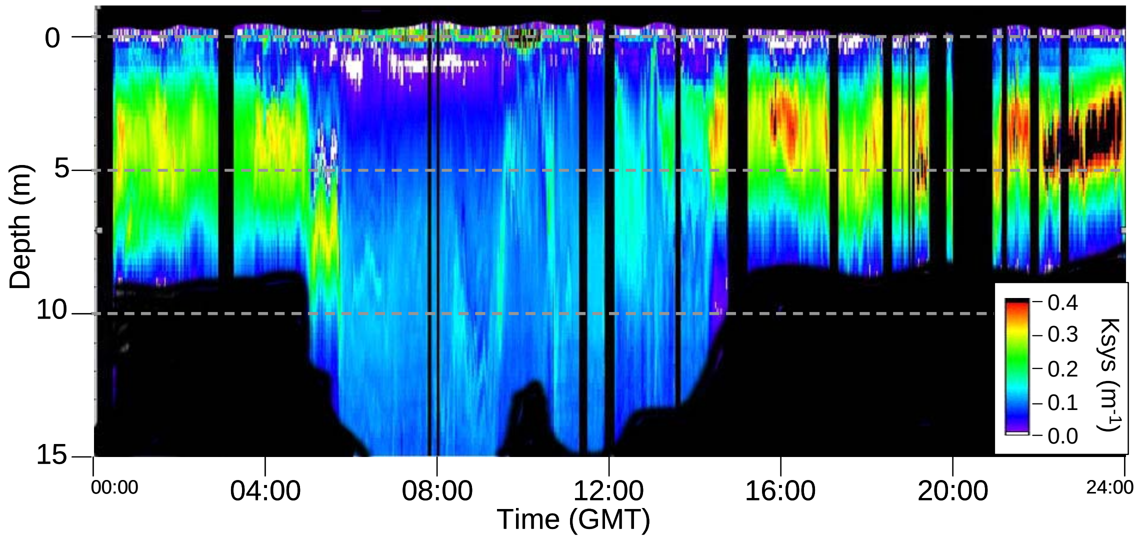

Figure 9. A color-coded Ksys Time vs. depth plot for the entire July 20th (GMT) period. Shows the various water types encountered. K_{sys} ranges from Blue = 0.0 m^{-1} to Red = 0.4 m^{-1}.

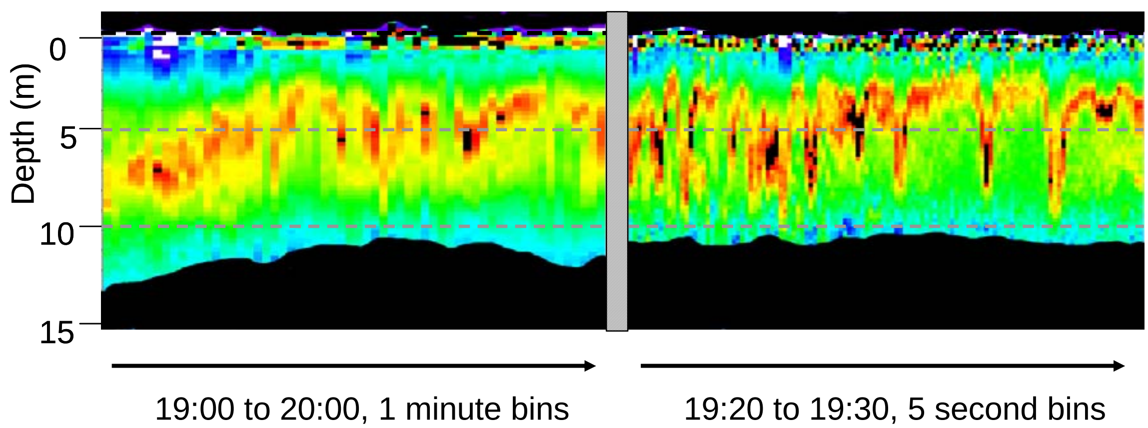

Figure 10. Two color-coded K_{sys} Time vs. Depth plots comparing time binning periods. On the left 60 minutes of data with 1 minute bins shows apparently random time varying vertical structures. On the right a 10 minute slice of the same data with 5 second bins shows periodic time varying structure due to internal waves.

For the 2006 Field test the SeaTROLL system was configured with two polarization sensitive receivers, one co-aligned and one cross-aligned to the linearly polarized laser transmitter. The expectation was to use the two channels to calculate the de-polarization rate of lidar signal to enhance scattering layer delectability and classify layer constituents. However in the field calculations indicated that the lidar signal was depolarized within a few meters of the surface. Post-field test laboratory experiments showed that the system maintained polarization sensitivity and further investigation is required to see if channel to channel comparisons can yield useful information.

In 2008, the lidar data set from the 2006 was imported into a MySQL database and is ready for further processing.

IMPACT/APPLICATIONS

This research directly relates to the Sensors and Environment areas itemized in Volume 2 of the study "Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st Century Force". This effort pushes a solution to provide oceanic IOP data for mission planning and sensor performance determination purposes over regional scale maritime areas. Deep optical data from littoral, strategic and homeland waters is a common tactical and environmental need for effectively using remote optical sensors, whether they are space based, airborne, ship based, or underwater.

TRANSITIONS

The SeaTROLL effort is relevant to the FY 07-9 OPNAV N88 development and demonstration of an active lidar system for anti-submarine warfare applications.

ENVIRONMENTAL COMPLIANCE

No harm to the environment occurred. Operations were conducted in accordance with the permit to operate in the Monterey Bay Sanctuary. No equipment was deployed for the lidar portion of the project and therefore no recovery operations were necessary.

RELATED PROJECTS

None.

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